Faculty of Mechanical Engineering

PRECEDING DEFORMATION EFFECTS ON THE CRUSH RESPONSE OF THE CIRCULAR CUP

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Master of Science in Mechanical Engineering

2018

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A thesis submitted
in fulfilment of the requirement for the degree of Master of Science
in Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITY TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I declare that this thesis entitled "Preceding Deformation Effects on the Crush Response of the Circular Cup" is the results of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : ………………………….....................................

Supervisor Name: Assoc. Prof. Dr. Sivakumar A/L Dhar Malingam

Date : …………………………………………………...

DEDICATION

To my beloved parents, my father Mohd Amman bin Hassan and my late mother Nurhaidah binti Bacho

To my loving and caring sisters, Nurhayati and Nurasyirah

To my beloved protecting brothers, Sabri, Muhammad Zulfadli, Mohd Asrul, Mohd Nur Azwan, Mohammad Hairul Nizam and Mohd Faqrul Ikhwashah

ABSTRACT

Automotive body structure is made up of formed components which have undergone plastic deformation during forming process that altered the structural behaviour of these components. Ignoring the preceding deformation effects in subsequent crush analysis could lead to inaccurate crashworthiness evaluation. In this study, the crush response of circular cup has been studied to quantify the effects of neglecting the preceding deformation effects such as geometrical changes and work hardening effects. The draw formed circular cups were fabricated through draw forming experiment on advanced high strength steel, dual-phase (DP600) steel with a nominal sheet thickness of 1.2 mm. Quasi-static crush experiment was subsequently performed on the draw formed circular cup to examine the preceding deformation effects on crush response. The draw forming simulation was performed at various punch speeds to investigate the geometrical changes and strain rates effect on deformation behaviour. An ideal computer-aided design (CAD) and draw formed cup model were used to developed finite element (FE) crush models in order to investigate the effects of geometrical changes and work hardening incurred during the draw forming process. The measured global load-displacement curve from experiments were used to validate the FE models developed using HyperWork. All draw forming and quasi-static crush experiments were simulated using Radioss solver employing Johnson-Cook constitutive model with isotropic hardening rule. The subsequent crush simulation was performed with and without incorporating mapped contour. Results show that draw forming process at various punch speeds affected the material strength and deformation behaviour of draw formed circular cup. In case of crush simulation without mapping (case A and case B), the geometrical changes from preceding draw forming process greatly affected the crush response of circular cup. The maximum force recorded at the end of crush process led to 46% and 15.2% higher for ideal CAD and draw formed cup geometry, respectively compared to the experiment. While in the case of with mapping (case 1 and case 2), work hardening effect resulted from draw forming process overcame the thinning effect and therefore made the structure stiffer and led to higher force value when compared to the case of without mapping. The percentage difference of maximum load recorded at the end of crush analysis with and without mapped residual contour was 12.9% and 3.8% for ideal CAD and draw formed cup model, respectively. Dynamic crush event showed higher response compared to quasi-static crush event in terms of load-displacement, stress and energy absorption behaviour by 45.5%, 40.7% and 30.7% respectively due to strain rates and inertia effects. Based on the crush response of the circular cup, the preceding deformation effects should be included in subsequent crush analysis by mapping the residual contour on draw formed geometry, instead on ideal CAD geometry in order to improve crashworthiness prediction.

ABSTRAK

Struktur badan automotif terdiri daripada komponen yang terbentuk yang telah mengalami pembentukan plastik semasa proses pembentukan yang mengubah tingkah laku struktur komponen-komponen ini. Mengabaikan kesan pembentukan terdahulu dalam analisis mampatan seterusnya boleh membawa kepada ketidaktepatan penilaian keupayaan kenderaan untuk mengelakkan kecederaan penumpang semasa kemalangan. Di dalam kajian ini, tindak balas mampatan cawan bulat telah dikaji untuk mengukur kesan mengabaikan pembentukan terdahulu seperti perubahan geometri dan kesan pengerasan kerja. Cawan bulat yang terbentuk dihasilkan melalui eksperimen pembentukan pada kepingan besi termaju berkekuatan tinggi, besi dwi-fasa (DP600) dengan ketebalan 1.2 mm. Eksperimen pemampatan kuasi-statik kemudiannya dilakukan pada cawan bulat yang terbentuk untuk meniliti kesan pembentukan terdahulu pada tindak balas mampatan. Simulasi pembentukan dijalankan pada pelbagai kadar muatan untuk menyiasat perubahan geometri dan kesan kadar terikan pada sifat pembentukan. Model reka bentuk ideal CAD dan cawan yang terbentuk digunakan untuk membangunkan model unsur terhingga (FE) mampatan. Lengkuk beban-anjakan global diukur daripada eksperimen digunakan untuk mengesahkan model yang telah dibina menggunakan HyperWork. Semua eksperimen pembentukan dan pemampatan kuasi-statik disimulasikan menggunakan model menjuzuk Johnson-Cook bersama dengan peraturan pengerasan isotropik. Simulasi pemampatan seterusnya dilakukan dengan dan tanpa menggabungkan pemetaan kontur. Hasil menunjukkan bahawa proses pembentukan pada pelbagai kadar muatan mempengaruhi kekuatan bahan dan sifat pembentukan cawan bulat yang telah terbentuk. Di dalam kes simulasi mampatan tanpa pemetaan (kes A dan kes B), perubahan geometri dari proses pembentukan terdahulu sangat mempengaruhi tindak balas pemampatan cawan bulat. Daya maksimum yang direkodkan pada akhir proses pemampatan membawa masing-masing kepada 46% dan 15.2% lebih tinggi untuk geometri ideal CAD dan cawan yang terbentuk, berbanding eksperimen. Manakala dalam kes dengan pemetaan (kes 1 dan kes 2), kesan pengerasan kerja yang terhasil daripada proses pembentukan mengatasi kesan penipisan dan mengakibatkan struktur menjadi lebih keras dan membawa kepada daya yang tinggi jika dibandingkan dengan kes tanpa pemetaan. Perbezaan daya tertinggi yang terhasil pada akhir prosess pemampatan dengan dan tanpa pemetaan sisa kontur adalah masing-masing 12.9% dan 3.8% untuk model ideal CAD dan cawan yang terbentuk. Pemampatan dinamik menunjukkan tindak balas yang lebih tinggi berbanding pemampatan kuasi-statik dari segi beban-anjakan, tegasan dan penyerapan tenaga masing-masing 45.5%, 40.7% dan 30.7% disebabkan oleh kadar terikan dan kesan inersia. Berdasarkan tindak balas mampatan cawan bulat, kesan pembentukan terdahulu perlu dimasukkan ke dalam analisis pemampatan seterusnya dengan memetakan sisa kontur kepada geometri cawan bulat yang telah terbentuk, bukannya pada geometri ideal CAD.

ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my main supervisor Associate Professor Dr. Sivakumar A/L Dhar Malingam from Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for his essential supervision, guidance, moral support and encouragement towards the completion of this thesis.

Besides that, I also would really like to express my greatest gratitude to Dr. Ismail bin Abu Shah from Faculty of Engineering Technology, my co-supervisor of this project for sharing his knowledge with me and always giving me many meaningful advices that was really inspired me throughout conducting this project. I appreciate all his contributions of time and ideas to make my MSc experience productive and stimulating. Special thanks to my ex-supervisor Dr. Haryanti Samekto for being my mentor which always gives me positive energy, encourage me and show me a path in achieving my ambition to further my study.

I would also like to express my deepest gratitude to Encik Mohd Faizal bin Halim, our project's group leader for sharing his knowledge about this project. This work has been also partly performed with a financial grant from the Research Acculturation Grant Scheme (RAGS/1/2014/TK01/FTK/B00083), which is gratefully acknowledged for its financial support. Also special appreciation to Encik Saiful Naim bin Sulaiman and support team from ORS Technologies Sdn Bhd for their guidance and assistance in helping me on my simulation, model set up and analysis works. Last but not least, I would like to thanks to Encik Wan Saharizal bin Wan Harun, our friendly technician who always helps and guiding me when conducting my experimental works. Besides that, I also like to thank all my friends especially Noordiana binti Mohd Ishak, Kathiravan A/L Subramaniam, Ng Lin Feng, Fadzila binti Hussain and Naziatul Fazilah binti Mohd Zalani for supporting me in different ways during my study.

My special thanks go to my late mother, beloved father and siblings for their continuous moral support in completing this master. Thank you to everyone who had been involved either directly or indirectly on completing this project.

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LIST OF ABBREVIATIONS

AHSS	-	Advanced High Strength Steel
ASTM	-	American Society for Testing and Materials
BHF	-	Blank Holder Force
BIW	-	Body in White
CAD	-	Computer-Aided Design
CEM	-	Crash Energy Management
CP	-	Complex phase
CPU	-	Central Processing Unit
CS	-	Cowper-Symond
DAD	-	Double Action Draw
DP	-	Dual Phase
FE	-	Finite Element
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
FLD	-	Forming Limit Diagram
HSLA	-	High Strength Low Alloy
HSS	-	High Strength Steel
IF	-	Interstitial-Free
IGES	-	Initial Graphics Exchange Specification
JC	-	Johnson-Cook
LCS	-	Low Carbon Steels
MS	-	Martensite steels
MIROS	-	Malaysia Institute of Road Safety Research
TRIP	-	Transformation induced plasticity
UTM	-	Universal Testing Machine
ZA	-	Zerilli-Armstrong

LIST OF PUBLICATIONS

JOURNAL:

1. Amman, R. M., Sivakumar, D., Abu-Shah, I. & Halim, M. F., 2018. Effects of Mapping on the Predicted Crash Response of Circular Cup-Shape Part. *Science & Technology Research Institute for Defence*, 11 (1), pp. 25-35.

2. Amman, R.M., Halim, M.F., Sivakumar, D., Abu-Shah, I., Sulaiman, S.N., Samekto, H. & Subramonian, S., 2018. Influences of Draw Forming Process on the Crash Analysis of a Circular Cup. *Journal of Advanced Manufacturing Technology*, 12, 1(2), pp. 547-560.

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1. Amman, R. M., Halim, M. F., Sivakumar, D., Abu-Shah, I., Sulaiman, M.S. & Samekto, H., 2016. Study of thinning effect from deep drawing process on crash analysis. *Proceedings of Mechanical Engineering Research Day (MERD2016).* Melaka, Malaysia, pp. 37-38, March 2016. UTeM.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter presents the introduction and overview of the topic and contents covered in this thesis. This includes the background of the study, problem statement, research objectives, the scope of the study, significance of findings and thesis layout.

1.2 Background of Study

In a study done by the Malaysia Institute of Road Safety Research (MIROS), it was found that the rate of road accidents in Malaysia is increasing annually with no sign of reduction (Abidin et al. 2012; Sarani et al. 2012). According to the United Nations World Health Organization's Global status report on road safety (Toroyan 2013; Toroyan 2015), Malaysia is the top among the Asian countries for having the highest road fatalities per 100,000 populations. For many years, road safety has become an international concern. Structures which operate under the risk of impact loadings, such as aircraft and vehicles, should consider the degree that able to protect the occupants from the effects of an accident which called crashworthiness. Crashworthiness is an ability of a structure to absorb the impact energy during collision or crash by controlled plastic deformations so that the energy transferred to the occupants will be minimized.

Nowadays, crash safety is an important issue in the automobile industry. It is very costly to study the crash event experimentally since it requires a lot of materials and many sensors to record huge data of impact loading. Therefore, since 1980's, crash studies by using numerical simulation has been intensively applied with the aim of reducing both time and money (Schweizerhof et al. 1992). However, finite element (FE) simulation demands highly specialized analysts and super-computer processing power. Today, all advanced commercial FE software, such as Ls-Dyna, Abaqus, and HyperWorks, have the capabilities to simulate a transient dynamic condition in impact loading. Finite element method (FEM) has been extensively used to reduce the development time of a vehicle as well as to predict the crashworthiness or safety level of vehicles (Doğan 2009).

In current industrial practice of a crash simulation conducted in automotive industries, material is treated as the way it was delivered. This is because material does not undergo any mechanical or heat treatments. However, in reality, a deformed shape part has experienced significant changes of physical and mechanical properties which can influence the later crash response. The most obvious effects are thickness variation, residual stresses and strain effects which have an influence on the subsequent structural analysis such as crashworthiness assessment, fatigue life prediction, stiffness evaluation and structural strength evaluation (Wu-rong et al. 2009).

Figure 1.1 shows components that are used to build a car body structure made from different types of material. These automotive components are produced by different manufacturing process such as hydroforming and stamping which involve plastic deformation process. As can be seen, these structural components have undergone plastic deformation during metalworking affect the later crash response. It has been shown that incorporating these effects in the subsequent crash simulation of stamped components is important (Williams et al. 2010).

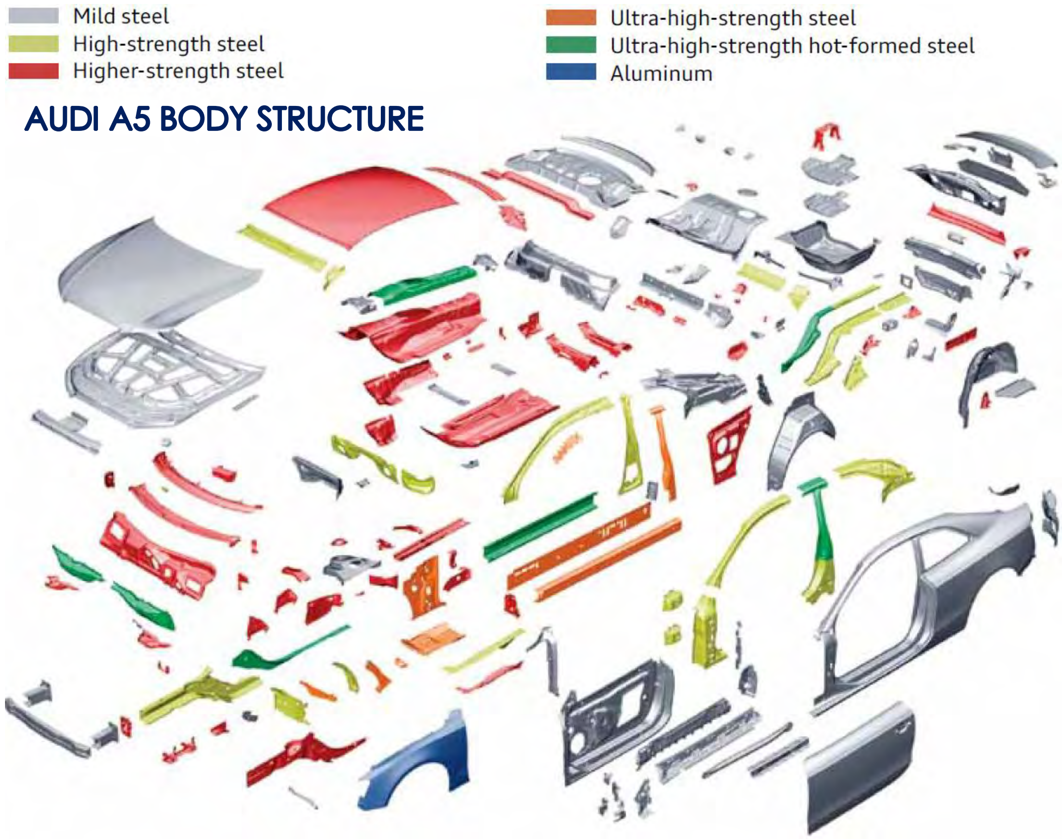

Figure 1.1: Components of AUDI A5 body structure (Kilic & Ozturk 2014)

As for lightweight vehicles, to ensure sufficient protection to the occupants during a collision, the car body structures are developed by using advanced materials to increase the strength-weight ratio. This leads to the development of advanced high strength steel (AHSS) which nowadays has been intensively applied in the auto bodies. Many materials have evolved in order to meet the lightweight and safety requirement such as magnesium, aluminium, low carbon steel and composite (Taub et al. 2007; Ghassemieh 2011). AHSS is no exception and has also shown its potential in order to maintain its low weight and cost characteristics, besides ensuring the safety of an occupant when a collision occurs. AHSS inherent high strength allows for thinner structural components making it lighter and contributing to a more fuel efficient vehicle (Kuziak et al. 2008). Among many types of AHSS material, the dual phase (DP) steel can attain very high strength while retaining moderate ductility compared to other materials. Ferrite-martensite DP steels 600 (DP600 steel) which has the ultimate tensile strength greater than 600 MPa, are one of the most popular AHSS used in the current vehicle production (Yu et al. 2009) to meet the enhanced government regulations and safety standards (Dong et al. 2014). The microstructure combination makes the DP steels to exhibit good formability with high strength based from the combination of soft ferritic matrix (provides good elongation) and islands of hard martensite (provides high strength). These characteristics make them ideal for energy absorption during an automotive crash.

The focus of this study is to investigate the crush response of a simple circular cup made of DP600 steel formed by using draw forming process. This study will cover numerical analysis using FEM and experimental studies to verify the simulation results.

1.3 Problem Statement

In predicting the crashworthiness of a structural part, the current industrial finite element analysis (FEA) practice shows some disadvantages. Due to simplifications, the preceding deformation effects are often neglected in subsequent crush analysis and the advantage of mapping approach is still not fully appreciated among researchers. Dutton et al. (1999), Takashina et al. (2009) and Williams et al. (2010) investigated the forming effects on crash analysis without performing mapping process. The crush analysis commonly performed based on an assumption that the structural part has a uniform thickness, ideal geometrical shape and nominal mesh which are obtained directly from the computer-aided design (CAD) modelling process. Furthermore, the preceding residual stress and strain mapped contour of draw forming parts which make the change in work hardening are also not taken into consideration in the subsequent crush FEA. As a result, the actual crush testing which involve full vehicle structure does not get similar response when compared to FEA and thus lead to higher cost to repeat the crush test.